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VACUUM ARC SWITCHED INVERTER TESTS AT 2.5 MVA*

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ABSTRACT A mathematical analysis of the unloaded vacuum arc switch (VAS) inverter is undertaken; a key element in this analysis is the assumption of a constant voltage drop of 50 volts across each VAS while it is conducting. From this analysis a constant VAS-voltage model is developed to explain the VAS inverter operation. A comparison of data obtained from laboratory tests of the inverter is made with data obtained from this model, and agreement is found to be within 10% for up to 15 alternations.

INTRODUCTION High-frequency, high-power inverter circuits employing vacuum arc switches (VAS's) as the switching elements have been under development at the State University of New York at Buffalo (SUNYAB) for some time (1 - 7). The circuit used in this development is the series inverter shown in Figure 1. Several tests have been conducted on the inverter (3); using the results of these tests, a model of the inverter was developed as is described in the following paragraphs.

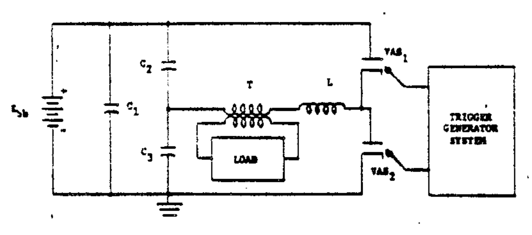

FIGURE 1. Series Vacuum Arc Switched Inverter.

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INVERTER CIRCUIT ANALYSIS The operation of the inverter circuit shown in Figure 1 has been described (6). In earlier work (1) the voltage drop across the VAS was measured and found to be nearly constant over a wide range of conducting currents. This characteristic suggests a constant V_{VAS} model for the VAS. Taking this characteristic into account, the capacitor voltages during the conduction of VAS_1 can be shown to be (4)

$$v_{C_1}(t) = \frac{C_3}{C_1+C_3}\left[V_{VAS_1} - V_{C_2}\left(\frac{n\pi}{\omega_1}\right)\right]\left\{1 + \frac{e^{-\sigma_1 t}[-\sigma_1 \sin(\omega_1 t) - \omega_1 \cos(\omega_1 t)]}{\omega_1}\right\} + V_{C_1}(n\pi/\omega_1), \quad (1)$$

$$v_{C_2}(t) = \left[V_{VAS_1} - V_{C_2}\left(\frac{n\pi}{\omega_1}\right)\right]\left\{\frac{e^{-\sigma_1 t}[-\sigma_1 \sin(\omega_1 t) - \omega_1 \cos(\omega_1 t)]}{\omega_1}\right\} + V_{VAS_1}, \quad (2)$$

and

$$v_{C_3}(t) = \frac{C_1}{C_1+C_3}\left[V_{VAS_1} - V_{C_2}\left(\frac{n\pi}{\omega_1}\right)\right]\left\{1 + \frac{e^{-\sigma_1 t}[-\sigma_1 \sin(\omega_1 t) - \omega_1 \cos(\omega_1 t)]}{\omega_1}\right\} + V_{C_3}\left(\frac{n\pi}{\omega_1}\right), \quad (3)$$

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14. ABSTRACT
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where $\sigma_1 = \frac{R_{CKT}}{2L}$,

$$\omega_1 = \sqrt{\frac{1}{LC_{T_1}} - \sigma_1^2},$$

and

$$C_{T_1} = C_2 + \frac{C_1C_3}{C_1+C_3},$$

all of for which

$$\frac{n\pi}{\omega 1} \le t \le \frac{(n+1)\pi}{\omega_1}, \quad n = 0,\ 2,\ 4,\ \cdots.$$

The equations for the capacitor voltages have a similar form for the conduction of VAS_2 (4). Now, the initial-final conditions between alternations take the following type of form:

$$V_{C_1}\left[\frac{(n+1)\pi}{\omega_1}\right] = V_{C_1}\left[\frac{m\pi}{\omega_2}\right],$$

$$V_{C_2}\left[\frac{(n+1)\pi}{\omega_1}\right] = V_{C_2}\left[\frac{m\pi}{\omega_2}\right],$$

and

$$V_{C_3}\left[\frac{(n+1)\pi}{\omega_1}\right] = V_{C_3}\left[\frac{m\pi}{\omega_2}\right],$$

where $m = 2k+1$,

$$n = 2k,$$

and k is the inverter output cycle number,

$$k = 0,\ 1,\ 2,\ 3,\ \cdots.$$

Equations (1) - (3), together with the initial-final conditions, comprise the Constant-V_{VAS} Model. A comparison will now be made between data obtained from this model and data obtained in the laboratory.

APPLYING THE MODEL Figure 2 shows an oscillograph of $v_{C_3}(t)$ obtained while the inverter was operating. In this particular test, the VAS's were pulsed alternately at a 1.04 kHz rate. The L-C combination of the circuit was resonant at 9303 Hz, so the transition time between the two polarities indicated on the oscillograph was about 54 usec. This left a delay of 0.9 msec before the next VAS was fired. This 0.9 msec delay appears in the oscillograph as the bright positive and negative peaks. This oscillograph suggests an approach to comparing data from the model with data from the test. The waveform in this oscillograph has a definite envelope; this envelope provides a good picture of the operation of the entire circuit, since, as the model equations show, an interdependence exists between all of the parameters of the circuit. Therefore, if the equations are obtained for the capacitor voltage envelopes, this form of the model will provide a basis for comparing the model with the data from the laboratory. The equations thus obtained are (4), for the positive peaks,

$$V_{C_1}\left[\frac{(n+1)\pi}{\omega_1}\right] = \frac{C_3}{C_1+C_3}\left[V_{VAS} - V_{C_2}\left(\frac{n\pi}{\omega_1}\right)\right]\left[1 + \exp\left(-\frac{\sigma_a}{\omega_a}\pi\right)\right] + V_{C_1}\left(\frac{n\pi}{\omega_1}\right), \tag{4}$$

$$V_{C_2}\left[\frac{(n+1)\pi}{\omega_1}\right] = -V_{C_2}\left(\frac{n\pi}{\omega_1}\right)\exp\left(-\frac{\sigma_1}{\omega_1}\pi\right) + V_{VAS}\left[1+\exp\left(-\frac{\sigma_1}{\omega_1}\pi\right)\right], \tag{5}$$

and

$$V_{C_3}\left[\frac{(n+1)\pi}{\omega_1}\right] = \frac{C_1}{C_1+C_3}\left[V_{VAS} - V_{C_2}\left(\frac{n\pi}{\omega_1}\right)\right]\left[1 + \exp\left(-\frac{\sigma_1}{\omega_1}\pi\right)\right] + V_{C_3}\left(\frac{n\pi}{\omega_1}\right), \tag{6}$$

again where

$$n = 0,\ 2,\ 4,\ 6,\ \cdots.$$

For the negative peaks, the equations become

$$v_{C_1}(t) = \frac{C_2}{C_1+C_2}\left[V_{VAS_2} - V_{C_3}\left(\frac{m\pi}{\omega_2}\right)\right]\left\{1 + \frac{e^{-\sigma_2 t}\left[-\sigma_2\sin(\omega_2 t) - \omega_2\cos(\omega_2 t)\right]}{\omega_2}\right\} + V_{C_1}\left(\frac{m\pi}{\omega_2}\right), \tag{7}$$

$$v_{C_2}(t) = \frac{C_1}{C_1+C_2}\left[V_{VAS_2} - V_{C_3}\left(\frac{m\pi}{\omega_2}\right)\right]\left\{1 + \frac{e^{-\sigma_2 t}\left[-\sigma_2\sin(\omega_2 t) - \omega_2\cos(\omega_2 t)\right]}{\omega_2}\right\} + V_{C_2}\left(\frac{m\pi}{\omega_2}\right), \tag{8}$$

and

$$v_{C_3}(t) = \left[V_{VAS_2} - V_{C_3}\left(\frac{m\pi}{\omega_2}\right)\right] \left\{\frac{e^{-\sigma_2 t}[-\sigma_2 \sin(\omega_2 t) - \omega_2 \cos(\omega_2 t)]}{\omega_2}\right\} + V_{VAS_2}, \quad (9)$$

where

$$\sigma_2 = \sigma_1 = \frac{R_{CKT}}{2L},$$

$$\omega_2 = \sqrt{\frac{1}{LC_{T_2}} - \sigma_2^2},$$

and

$$C_{T_2} = C_3 + \frac{C_1 C_2}{C_1 + C_2},$$

all of for which

$$\frac{m\pi}{\omega_2} \le t \le \frac{(m+1)\pi}{\omega_2}, \; m = 1, 3, 5, \dots.$$

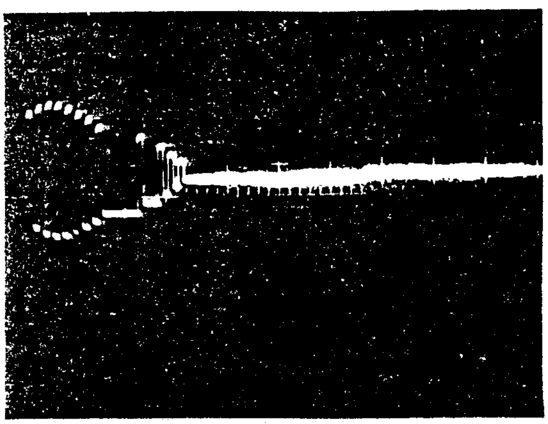

FIGURE 2. Oscillograph of $v_{C_3}(t)$ during Operation of the Inverter.

Equations (4) - (9) were used to calculate the succeeding initial-final conditions on the capacitors, assuming the same pre-charged voltages used in the laboratory tests (4), and 50 volts for V_{VAS}. Table 1 shows data extracted from Figure 2 compared with data obtained from the Constant-V_{VAS} Model. As can be seen, the envelope determined by the model matches quite closely the envelope obtained from the tests. Note that the envelope values determined by the model are within the estimated 10% accuracy of the test data out to the 15 alternation.

TABLE 1. Data for Comparison of Inverter Tests with the Model.

$V_{C_3}(n\pi/\omega)$ from tests (kV)	$V_{C_3}(n\pi/\omega)$ from V_{VAS}=50V (kV)	Alternation No. (n)
-1.00	-1.00	0
1.25	1.26	1
-1.05	-1.14	2
1.35	1.35	3
-1.15	-1.23	4
1.40	1.39	5
-1.20	-1.26	6
1.40	1.37	7
-1.20	-1.24	8
1.30	1.29	9
-1.10	-1.17	10
1.20	1.18	11
-1.00	-1.05	12
1.10	1.02	13
-0.90	-0.90	14
0.95	0.83	15
-0.75	-0.71	16

TABLE 2. Values of Inverter Components.

Component	Value
C_1	960µF
C_2	4.89µF
C_3	4.89µF
L	30µH
R_{CKT}	23.2mΩ

The component values used in Equations (4) - (9) in calculating the data points listed for the model in Table 1 had been obtained in earlier tests (3), and are listed in Table 2.

CONCLUSIONS For the VAS operating in a series resonant inverter, the use of a Constant-V_{VAS} Model to represent the dynamic characteristics of the VAS is a valid approximation for high power (2 - 2.5 MVA) operation. Further tests are therefore warranted at other operating power levels.

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